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EVIDENCE FOR A COLLISION-FREE MAGNETOHYDRODYNAMIC SHOCK IN INTERPLANETARY SPACE

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A rapid, apparently irreversible change in the interplanetary plasma and magnetic field was seen on 7 October 1962 by Mariner II when it was 10.6×10^6 km from earth and 36° to the left of the earth-sun line as seen by an earth observer facing the sun. The geometry of the spacecraft on the occasion of this event is shown in Fig. 1. The unit vectors are $\vec{e}_R, \vec{e}_N, \vec{e}_T$ such that $\vec{e}_R$ is radially outward from the sun; $\vec{e}_N$ is directed toward the ecliptic north pole, and $\vec{e}_T=\vec{e}_N\times\vec{e}_R$ is in the direction that the earth moves. This event appears to be a hydromagnetic shock with

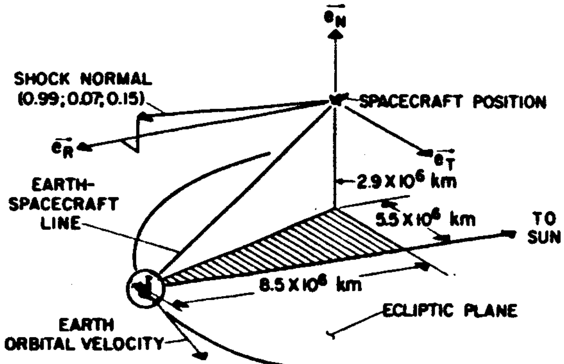

FIG. 1. Geometry of the Mariner II orbit on 7 October 1962. The shock normal direction computed from the change in the magnetic field is indicated. $\vec{e}_R, \vec{e}_N, \vec{e}_T$ are unit vectors defining a coordinate system along the radius vector from the sun, toward the ecliptic north pole, and along $\vec{e}_N\times\vec{e}_R$, respectively.

a structure that is vanishingly thin compared to the mean free path. Theoretical investigation of such shocks has predicted structures whose scale is determined by the gyroradii.[1] The potential importance of such shocks in interplanetary space has been discussed by Gold[2] and Parker.[3]

The general character of the interplanetary medium is known from the analyses of magnetometer and plasma data, the latter having been summarized by Neugebauer and Snyder[4] and by Snyder and Neugebauer.[5] The plasma data for this event show that the flux dropped to an undetectable level in the 314-km/sec channel, decreased somewhat in the 379-km/sec channel, and increased substantially in the 464-, 565-, and 689-km/sec channels. These changes occurred during one sampling interval of the plasma probe (3.7 min). Simultaneously, the magnetic field (Fig. 2) displayed a pulselike rise in magnitude from 6 to 16 γ ($1\ \gamma=10^{-5}$ gauss), followed immediately by a partial relaxation to about 11 γ and the appearance of disordered fields lasting many hours.

A sudden-commencement geomagnetic storm began at the earth 4.7 hours later. Assuming that a spherical pulse expanded outward from the sun, the corresponding radial velocity was 510 km/sec ($=10.6\times10^6\cos36°/4.7\times60^2$). From the plasma data, the pre- and post-event solar wind velocities, assumed to be radially out from the sun, are 380 ± 10 km/sec and 460 ± 10 km/sec,[6]

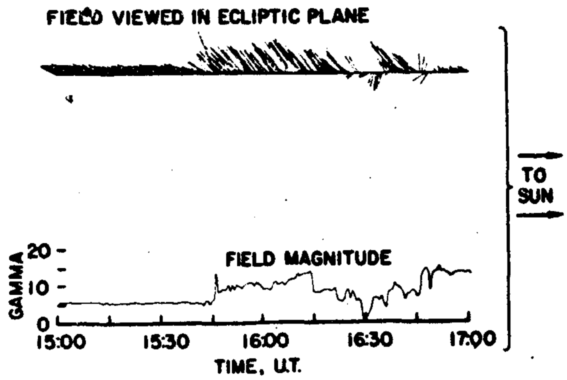

FIG. 2. Magnetic field recorded by Mariner II magnetometer for a two hour period, 7 October 1962. Spike marking the event is at 1546 UT.

respectively. In the Mariner coordinate system, the solar wind velocities on both sides of the event are highly super-Alfvénic and supersonic; however, in a frame of reference moving with the wind, the velocities imply a shock of low Mach number.

To test the identification as a shock, we investigate the abruptness of the magnetic pulse (Fig. 2). If a smooth curve is drawn through the data, it appears that the structure may just be resolved. A disturbance velocity of 510 km/sec implies a pulse thickness of perhaps 3×10^4 km. It is implausible that the pulse is an ordinary, large-amplitude wave because such a short wave should rapidly steepen into a shock with a thickness determined by dissipative processes and the gyroradii. Although structures smaller than 2×10^4 km could not be detected with the telemetry sampling interval of 37 seconds, the irregularity of the data points suggests that such structure may be present. If the waves of elementary collisionless shock theory[1] are involved, the characteristic dimensions of the smallest scale features should be of the order of 2 km. The data are consistent with a shock composed of a superposition of such waves, organized into the larger scale pulse shown in Fig. 2 by dissipative phenomena. Since viscosity and thermal conductivity cannot operate in a time less than one collision period, the observed narrow pulse may suggest that plasma instabilities damp the waves.

Further support for interpreting the event in question as a shock is provided by showing that the data are consistent with the well-known[7] high-conductivity hydromagnetic generalization of the single-fluid, isotropic-pressure, Rankine-Hugoniot conditions that express conservation of mass, momentum, and energy. It is assumed that in the shock frame of reference, conditions are stationary and all velocity, magnetic, and electric fields are uniform in each of the two regions separated by the shock front. The data do not show this uniformity after passage of the shock front; hence, we use the best available average values and suggest that the fluctuations be regarded as a form of internal energy to be allowed for by use of a suitable effective value of γ, the ratio of specific heats.

The values of $\vec{B}_1$ and $\vec{B}_2$, magnetic fields just before and just after the shock passes by, allow a determination of the shock normal. $\mathrm{Div}\vec{B}=0$ requires that the plane of the shock contain $\Delta\vec{B}=\vec{B}_2-\vec{B}_1$. The Rankine-Hugoniot conditions derived from the conservation of the transverse component of the momentum, and the continuity across the shock front of the tangential component of the electric field in the shock reference frame, require that the shock normal lie in the plane of $\vec{B}_1$ and $\vec{B}_2$. Hence, the shock normal must be perpendicular both to $\Delta\vec{B}$ and to $\vec{B}_1\times\vec{B}_2$. Since the solar wind flows nearly radially outward from the sun, it might be expected that the shock normal would be in the radial direction. The Mariner-II observations show that $\Delta\vec{B}$ had a substantial radial component; hence the shock front must be oblique, with the usual consequence of a refraction of the plasma velocity vector in passing through the shock front. It should be emphasized that this conclusion is not affected by any uncertainty in our knowledge of the spacecraft field (the magnetometer cannot distinguish between interplanetary fields and those of the spacecraft) because the spacecraft field affects $\vec{B}_1$ and $\vec{B}_2$ equally and does not affect $\Delta\vec{B}$.

The heliocentric velocity with which one must move in a direction normal to the shock front in order to remain in it is

$$v_n=\vec{r}_{ME}\cdot\vec{e}_S/t, \tag{1}$$

where $\vec{r}_{ME}$ is the vector from Mariner to the earth, $\vec{e}_S$ is the shock normal unit vector, and $t=4.7$ h is the time between the event on Mariner and the sudden commencement of the geomagnetic storm. As the shock reference frame, let us use a system whose origin moves along $\vec{e}_R$ with the velocity

$$v_{SR}=v_n/\vec{e}_S\cdot\vec{e}_R=509\ \mathrm{km/sec}, \tag{2}$$

which keeps the origin in the shock front. As axes in this frame, use the mutually orthogonal unit vectors $\vec{e}_\beta$ along $\Delta\vec{B}=0.9\vec{e}_R-5.6\vec{e}_T-3.9\vec{e}_N$,

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$\hat{e}_\alpha$ along $\vec{B}_2\times\vec{B}_1$, and $\hat{e}_\gamma=\hat{e}_\alpha\times\hat{e}_\beta=\hat{e}_s$, as given in Fig. 1. Since $\vec{B}_1$ and $\vec{B}_2$ are normal to $\hat{e}_\alpha$, the shock conditions are simplified in this system. The plasma probe data show that the preshock gas has a heliocentric velocity of $380\hat{e}_R$ km/sec, where we disregard the possibility of very small transverse velocities. In the shock frame the components are $v_{\alpha 1}=9$ km/sec, $v_{\beta 1}=-17$ km/sec, $v_{\gamma 1}=128$ km/sec.

It is assumed in the sample calculation that the preshock gas density is 15 cm^{-3}. This is the best value from Neugebauer[8]; it assumes an isotropic temperature distribution and takes the aberration due to spacecraft motion into account. The components in the shock frame of the pre- and post-shock magnetic fields given above are $B_{\alpha 1}=B_{\alpha 2}=0$, $B_{\beta 1}=4.9\ \gamma$, $B_{\beta 2}=11.8\ \gamma$, and $B_{\gamma 1}=B_{\gamma 2}=4.1\ \gamma$.

A summary of the results of the application of the Rankine-Hugoniot equations is given in Table I.

Ordinarily one assumes that T_1, the upstream temperature, and the direction of the shock normal are known and solves the equations for all the conditions on the downstream side of the shock. Instead, we assume that the downstream magnetic field is known and solve for the shock normal, the temperatures on both sides of the shock, and the velocity and density on the downstream side. With the data given above and the ratio of specific heats $\gamma=\frac{5}{3}$, we get in the heliocentric frame $\vec{v}_2=450\hat{e}_R+10\hat{e}_T+14\hat{e}_N$, i.e., in a direction 1.3° westward and 1.8° to the north of $\hat{e}_R$. The density is about 34 cm^{-3}; the temperatures can be fitted to $T_1\approx 10^{5.0}$ and $T_2\approx 10^{5.4}$ °K; and the shock strength is about 4.

We must now compare these predictions of our sample calculation with observation where $\vec{v}_2$ is modified by solar wind aberration. The magnitude of $\vec{v}_2$ agrees well with the plasma data, which give no direct information on the change in direction. The values of density and temperature are somewhat higher than those generally found by Neugebauer.[8] More precisely, it is not possible to fit both T_1 and T_2 for any value of γ. In choosing to make T_1 equal to that found by Neugebauer and constraining γ to $\frac{5}{3}$, T_2 is higher by half than the isotropic extension of the experimental post-shock gas temperature. There is considerable fluctuation in the observed quantities. If the fluctuations over which we average involve substantial amounts of internal energy, γ should be decreased and this will decrease the computed temperature difference. We conclude that the data fit this model of a shock to within the uncertainties in the data.

We expect to refine these calculations in a subsequent paper, where the effect of varying γ will also be considered; and we emphasize here the qualitative evidence for a hydromagnetic shock.

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[1]J. H. Adlam and J. E. Allen, Phil. Mag. 3, 448 (1958); L. Davis, Jr., R. Lüst, and A. S. Schlüter, Z. Naturforsch. 13a, 916 (1958); J. W. Dungey, Phil. Mag. 4, 585 (1959).

[2]T. Gold, Gas Dynamics of Cosmic Clouds (North-Holland Publishing Company, Amsterdam, 1955), Chap. 17, p. 103.

[3]E. N. Parker, Interplanetary Dynamical Processes

Table I. Measured and computed gas parameters: pre- and post-shock values for $\gamma=\frac{5}{3}$. Shock velocity is $509\hat{R}$ based upon transit time and computed shock normal direction.

Parameter	Preshock Measured	Post-shock Computed	Post-shock Measured
$B(10^{-5}$ gauss)	$5\hat{R}-3.7\hat{T}-2.2\hat{N}$	...	$5.9\hat{R}-9.3\hat{T}-6.1\hat{N}$
V(km/sec)	$380\hat{R}$	$450\hat{R}+10\hat{T}+14\hat{N}$	$458\hat{R}$
$N(cm^{-3})$	15 ± 2	34	32 ± 4
T(°K)	1.2×10^5 (measured) 1.1×10^5 (computed)	2.4×10^5	1.7×10^5
Magnetoacoustic Mach No.	2.0	0.7	0.6

(Interscience Publishers, Inc., New York, 1963).
[4]M. Neugebauer and C. W. Snyder, Science 138, 1095 (1962).
[5]C. W. Snyder and M. Neugebauer, Fourth International Space Science Symposium (Cospar), Warsaw, 1963 (unpublished).
[6]The post-shock gas velocity used is that when the magnetic field appears to have stabilized to its new value after the initial pulse has passed.
[7]W. B. Thompson, An Introduction to Plasma Physics (Pergamon Press, New York, 1962), p. 92.
[8]M. Neugebauer, private communication.

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